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Applied levelized cost of electricity for energy technologies in a small island developing state: A case study in Mauritius

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ABSTRACT

As climate change accelerates, many countries most vulnerable to its effects are leading by example by transitioning to renewable energy economies. One example is in Mauritius, a small island developing state with admirable goals of increasing renewable generation but struggling to achieve them cost-effectively. This research assists Mauritius by identifying local renewable resource potential and island specific costs to determine the levelized cost of electricity (LCOE) of various technologies. Solar and offshore wind are determined to yield above average energy potential, wave, sugar cane trash, and municipal solid waste-to-energy average potential, onshore wind below average potential, and hydro-power and geothermal unfeasible potential. Each renewable energy system's energy potential is directly tied to its capacity factor, which was determined to be the most impactful levelized cost of electricity (LCOE) variable in Mauritius. The LCOE for bagasse generation, landfill gas-to-energy, and utility-scale solar PV are below coal's LCOE, fuel oil's operating costs, and the average consumer cost of electricity. Therefore, even without considering fossil fuels' indirect environmental and health costs, multiple renewable energy technologies are shown to be more cost-competitive than fossil fuels in Mauritius. Policy makers in Mauritius can utilize this direct LCOE analysis to confidently prioritize cost-effective solutions.

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1. Introduction

Countries around the world are transitioning to renewable energy systems to improve public health, reduce impacts on climate change, and increase energy independence. Being a small island developing state (SIDS) more vulnerable to climate change, Mauritius has recently taken multiple steps to begin their transition to a renewable energy economy. In 2009, Mauritius committed to increasing renewable generation from 20% to 35% by 2025 [1], was ranked 2nd in the world in 2014 for renewable energy investment per GDP [2], and created the Mauritius Renewable Energy Agency (MARENA) in 2015. However, in 2017, Mauritius still generated only 21% of its electricity from renewable sources – 15% bagasse, 2.9% hydro, 2.4% solar PV, 0.5% onshore wind, and 0.5% landfill gas (LFG) – partly due to an ever increasing electrical demand of 2–4% per year [3]. The consumer cost of electricity (CCOE) also spiked in the late 2000s, seen in Fig. 1 [3], prior to the 2011 tariff structure, stemming from a high dependence on variable fossil fuel prices. Thus, an important focus has been placed on renewable technologies that can stabilize or lower consumer rates. Therefore, the goal of this research is first to assist Mauritius policy makers and its public utility, the Central Electricity Board (CEB), achieve its renewable energy goal by utilizing local levelized cost of electricity (LCOE) metrics to prioritize the most cost-effective technologies, and second to provide a model for other SIDS looking to cost-effectively transition to a clean energy economy.

Recent research using the LCOE metric has been done for various countries, large and small, to assist policy makers in making cost-effective decisions. For the SIDS Trinidad and Tobago, the LCOE was utilized for comparing the economics of various wind turbines to local fossil fuel generation [4]. However, more attention was taken on wind speed data verification and the energy generation aspect of the LCOE calculation, without providing Caribbean specific capital and operating costs, discounting future energy generation, or including turbine degradation. In a separate LCOE study of solar PV, onshore wind, and biomass systems in China, Ouyang used the “EGC Spreadsheet model” to factor in country specific

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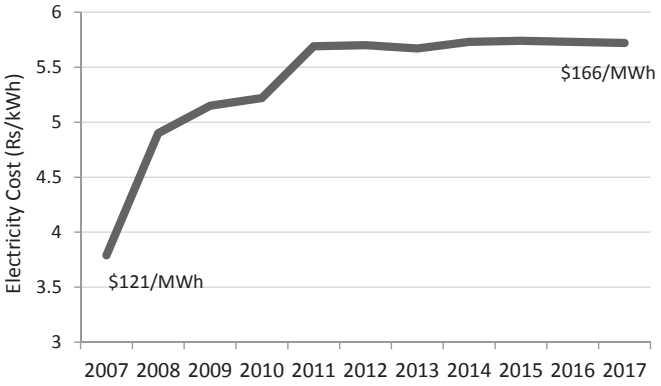

Fig. 1. Historical average consumer cost of electricity in Mauritius.

system costs and generation but failed to factor in system degradation [5]. Nevertheless, this study was useful in recommending specific subsidies and electricity pricing reform in China. Leal et al. also recommended energy system development in Brazil using a modified LCOE including costs of natural gas leakage, transmission, and carbon costs to compare the economics of various thermoelectric plants [6]. Hernández-Moro et al. [7] developed a mathematical model for solar electricity costs based on the LCOE and discounted cash flows, and concluded that, for PV systems, the LCOE and its evolution is practically proportional to the initial cost of the systems. One important take-away from all these studies is the LCOE's high variability and dependence on local conditions. Therefore, this paper focuses on obtaining Mauritius specific costs and renewable resource data to accurately determine the local LCOE and assess the cost-competitiveness of renewable energy systems in Mauritius.

The methods taken to obtain the local LCOE inputs, and calculate the corresponding LCOE, are first outlined. The resulting cost inputs and resource potential are then analyzed and compared to the global market. Each technology's LCOE is also compared to the global market, but more importantly compared to each other to highlight the most cost-effective technologies and conclude the most cost-effective path forward. A sensitivity analysis identifies the most impactful input variables, and steps to limit their variability are proposed. Lastly, the limitations of this study are addressed, and additional research outside this paper's scope, but necessary in holistic and proper renewable energy planning, is suggested.

2. Methodology

To ensure that the LCOE best reflects local conditions, special attention to detail was taken in obtaining data that accurately reflects local energy resources and the local market. The overall process flow in obtaining this information is represented in Fig. 2. A literature review of recent renewable energy assessments in Mauritius was conducted and, when available, energy data was collected to calculate each technology's energy potential, capacity factor (CF), and corresponding annual electric generation. The sources of data used in the study are elaborated in the following sections. For cost inputs, data is specified in coming from either local operating plants or international reports. Applying this local data to the LCOE equation yields country-specific results and allows for direct comparison between energy systems. Lastly, a sensitivity analysis identifies the degree to which variables affect each technology's LCOE.

2.1. Resource potential & capacity factor

Renewable energy resource potential varies widely globally and even regionally based upon various factors of each climate. While solar irradiance can be similar, wind speeds, wave patterns, geothermal heat sources, rainfall, and even soil quality for biomass can vary from island to island. Therefore, utilizing quality data specific to Mauritius proves especially important in determining the relative energy potential of each source.

For solar PV, solar irradiance was collected at 30-s intervals from five c-Si reference cells placed in the north, south, center-west, center-east, and east by University of Mauritius researchers. The most recent 2017 irradiance data was obtained to update their previously published data [10]. To account for the west, south-west, south-east, and center regions, their irradiance was estimated using their sunshine hour data obtained from Mauritius meteorological services to interpolate between two locations with known irradiance, I, and sunshine hour data, SH, as shown in equation (1).

$$I_C = I_A + \frac{SH_C - SH_A}{SH_B - SH_A}\, x\, (I_B - I_A) \tag{1}$$

This technique was verified by cross-checking generation data at one solar PV farm at a location whose data was interpolated. A solar map was then generated using GIS software to visualize solar resource potential across the island.

NREL's PV Watts software was then utilized to calculate the percentage increase in irradiance for a fixed tilt system at an angle equal to Mauritius' latitude, and a single-axis tracking system. The final direct-current (DC) CF range was determined by dividing the total annual insolation by hours in a year. For annual energy generation, E_0, the capacity factor, CF, was multiplied by the solar PV farm's AC rated output power, Cap_{AC}, which takes into account inverter and other system losses, by hours in a year, as shown in equation (2).

$$E_0 = Cap_{AC} \times 8760 \times CF \tag{2}$$

Wind speed data was taken from a wind resource map developed by University of Mauritius researchers using computational fluid dynamic software, WindSim 6.0, to assess wind speeds over Mauritius' complex and rough terrain [11]. They used data from nine wind measuring stations, obtained at 3-hourly intervals over a 2 year period, as their inputs to create wind maps at heights of 10, 33, 66, and 110 m. These height specific wind speeds were applied to the power curves of wind turbines used at each site to determine final CF ranges.

Offshore wind power density and wave energy density data was obtained from the Mauritian Research Council's (MRC) preliminary offshore wind and wave energy map [12]. Its wave data, taken at 20-min intervals from 2002 to 2011 at 23 sea stations at various depths along the coast, was confirmed by Carnegie Clean Energy's 6 month wave buoy on the south-eastern coast. Applying this data to IEA's Ocean Energy System's CF graph estimates a gross CF, and using 16% losses, based on offshore wind [13], yields a net CF for wave. In the same MRC study, offshore wind speeds from satellite imagery were utilized in calculating its power density. Based on this data, CF estimates were determined by utilizing the expertise of an offshore wind professional with an understanding of the Mauritian context.

As Mauritius looks to address municipal solid waste (MSW) disposal, its energy potential can be exploited through waste-to-energy (WtE) combustion applications like gasification or incineration, and LFG plants. For energy potential, E_{MSW}, in kWh per ton through gasification or incineration, the treated caloric value, CV, in MJ per kg of MSW, based on research from a potential gasification

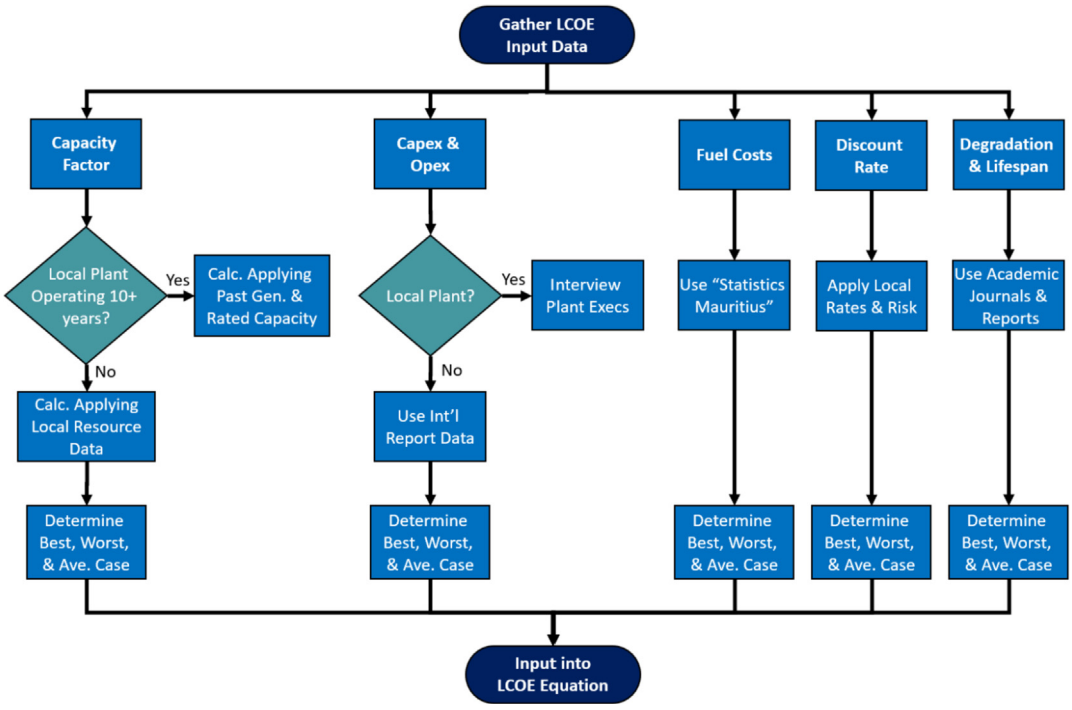

Fig. 2. LCOE methodology process flow.

plant developer in Mauritius, was converted to kWh per ton and then multiplied by the likely plant availability, A, and efficiency, η, as seen in Equation (3).

$$CV \times \frac{1000\ kWs}{1\ MJ} \times \frac{1000\ kg}{ton} \times \frac{1hr}{3600\ s} \times A \times \eta = \mathrm{E_{MSW}} \tag{3}$$

Since waste treatment removes moisture and undesired material, the annual tons of untreated MSW, $T_{unsorted,annual}$, must also be converted to the mass of treated waste, $T_{treated}$, to calculate its full energy potential, E_0, as seen in Equation (4). Its CF was then calculated by re-arranging Equation (2) and applying the power capacity of a planned gasification plant.

$$\frac{T_{unsorted,annual}}{year} \times \frac{T_{treated}}{T_{unsorted}} \times \mathrm{E_{MSW}} = \mathrm{E_0} \tag{4}$$

For a LFG plant, its CF and corresponding energy generation were determined by combining actual annual generation data from Sotravic Ltd with estimated future gas generation data using LandGEM Software [14]. The actual electricity generation data was fit to annual gas production to estimate decreasing future energy generation after reaching capacity, as seen in Fig. 3. Average CFs for 10, 13, and 15 year lifetimes were determined using these future generation values, and it should be noted that the 'worst case scenario' involves a shorter lifetime of 10 years but higher average CF due to declining generation in the last few years.

The main form of biomass used for electricity in Mauritius is bagasse, the fibrous residue left over during the crushing and extraction of sugar from sugar cane stalks. While sugar cane farm land has been decreasing for decades due to development and the recent European Union sugar price reform [15], further potential still exists through plant centralization, improved power plant efficiencies [16,17], and utilization of cane trash left in the fields during cultivation. The increased energy potential from plant centralization and increased efficiency was identified in Alteo Ltd's annual report [18], and confirmed through a CEB representative. Cane trash potential was calculated by applying its caloric value and overall mass, identified in pilot projects from local sugar cane companies Terragen Ltd and Omnicane Ltd, and current bagasse plant efficiencies to Equation (3).

For solely bagasse, solely coal, and fuel oil plants, CF calculations were straightforward by dividing their historical 10 year average generation data by effective capacity. However, for bagasse-coal plants running at different seasonal capacities depending on their fuel input, their CF was calculated by inputting historical generation data into equation (5) [17–19].

$$\text{Net CF} = \frac{\frac{Bagasse\ MWh\ Generated}{Bagasse\ MW\ Capacity} + \frac{Coal\ MWh\ Generated}{Coal\ MW\ Capacity}}{8760\ hours/year} \tag{5}$$

Lastly, geothermal and hydropower potential was briefly investigated through past Mauritius' Ministry of Energy & Public Utilities reports and research [20]. Since their potential is unfeasible, as discussed in more detail later, they were not included in the LCOE analysis.

2.2. Capital & operating costs

Obtaining Mauritian specific capital and operating costs was important to accurately portray the local market. Two different methodologies were used to obtain these costs, one for real capex and opex from technologies currently operating in Mauritius and one to estimate costs for technologies not yet operating. Renewable energy systems' capex and opex were then compared to global averages from IRENA and IEA, and fossil fuel capex to global averages from the World Energy Council [21–24]. All costs were converted into 2018 USD using MUR and USD historical exchange rates and inflation.

For currently operating or nearly commissioned plants, capex and opex were obtained through either an in-person or phone interview with plant executives. For utility-scale fixed tilt and single-axis tracking solar PV, these were provided through

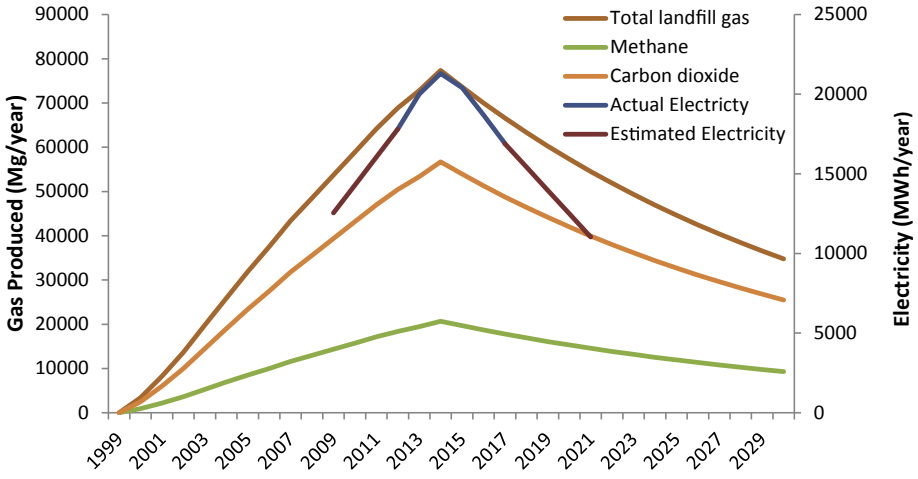

Fig. 3. Estimating Future LFG plant Electricity based on LandGEM Gas Estimates.

interviews with four private companies with recently signed Power Purchase Agreements (PPAs) with the CEB in 2016 and 2017, ranging from 5 to 13 MW capacity. Residential PV system costs were determined from price quotes from seven residential solar PV companies in Mauritius, ranging from 1 to 3.5 kW and differing in smart technology and panel chemistry. Inverter replacement costs, separate from opex, were included in years 13 and 26 of the system to convey future replacement costs [25]. Local onshore wind costs were provided through interviews with developers of the only two Mauritian wind farms signed in 2013, and to convey cost reductions since their signing a capex reduction of 14.2% was applied based on global historical capex reductions [24]. LFG capex and opex were identified through interviews with a representative from the Sotravic 3.3 MW LFG plant at the sole Mauritian landfill. Capex for bagasse-coal power plants, and solely coal plants, were based on investment numbers provided by plant personnel for the two most recent bagasse-coal plants constructed in 2000 and 2006, and solely coal fired plant in 2005. Capex for solely bagasse fired plants were assumed to be similar due to lack of data. Bagasse only, coal only, and bagasse-coal plants' opex were also assumed to be similar to the bagasse-coal plants, with one plant providing both fixed and variable costs, and the other only variable costs. A CEB interview provided fuel oil capex based on the 2017 60-MW St. Louis Power Plant redevelopment project, and opex for their three operating plants [26].

For new technologies like offshore wind, wave, and WtE gasification, costs were estimated through interviews with industry experts and research reports. For offshore wind, capex and opex estimates were obtained from interviews with the same experienced offshore wind developer as previously mentioned. Wave energy costs were obtained based on a combination of IRENA and IEA reports [21,22] and a developer's insights since no commercial scale wave energy arrays had been commissioned worldwide. MSW gasification plant costs were determined through cost estimates from a representative of a planned gasification plant in Mauritius and compared to global gasification averages to ensure accuracy [27].

2.3. Fuel costs

Fuel costs can represent a significant portion of thermal plants LCOE, but can also fluctuate considerably, so long term averages were obtained. Fuel usage for local coal plants was analyzed using plant annual reports and 10-year average fuel costs per ton from Statistics Mauritius [3]. A fuel cost, in $/MWh, was then calculated by dividing a plant's annual fuel costs by its annual generation. For bagasse-coal plants, fuel costs were calculated by dividing total annual coal cost and bagasse revenue by annual generation. For fuel oil's fuel cost range, the amount of fuel oil used for electricity production for the three local fuel oil plants was multiplied by their average fuel import cost from 2006 to 2014 [3]. Lastly, neither fuel costs nor revenues for WtE facilities were included since in Mauritius they do not have the typical advantage of being able to charge a gate fee per ton of waste received to generate additional revenue [23].

2.4. Other variables

In addition to energy potential and capacity factor, a technology's degradation rate and corresponding lifespan also affect its lifetime generation. Global average degradation rates for solar PV, wind, and wave were researched and utilized, as local conditions should not have a major impact on their local degradation [28–32]. For thermal plants, degradation rates and lifespans were determined from a combination of interviews with plant executives and reports in both academic and private sectors [31,33–37]. The last variable, discount rate, is important when considering the time value of money by discounting lifetime costs and generation. Applicable discount rates for technologies currently operating on island were determined through a combination of personal interviews with local project executives and discussions with Mauritian banks about local lending rates. Wave and offshore wind rates were estimated based on its relative risk, specifically economic, technical, political, and social risks.

2.5. Levelized cost of electricity

One of the difficulties in comparing the cost-effectiveness of various energy systems is factoring in large differences and complexities in each technology's installed costs, operating costs, financing, and energy generation. The LCOE is one of the most widely accepted metrics for analyzing an energy system's cost-effectiveness because it encompasses all these factors. Its net present value of cost per unit energy allows not only for direct comparisons of various technologies, but also provides a baseline price that an independent power producer (IPP) must receive for its asset to break even over its lifetime. And locally, their respective LCOE can also be compared to electricity rates to understand its cost-

competitiveness in the local market. While ways to compute the LCOE can vary from the desired accuracy and number of factors considered, the following equation falls in line with IRENA's recommended equation [38]:

$$\mathrm{LCOE} = \frac{\textit{Discounted Lifetime Costs}}{\textit{Discounted Lifetime Electricity}} = \frac{\sum_{t=0}^{T}(C_t + O_t + F_t) \Big/ (1+r)^t}{\sum_{t=0}^{T} E_0(1-d)^t \Big/ (1+r)^t} \quad (6)$$

where:

C_t = capital investment expenditures in year t (Capex)
O_t = operation and maintenance expenditures in year t (Opex)
F_t = fuel expenditures in year t
E_0 = rated electricity generation in the first year
d = degradation rate
r = nominal discount rate
T = life of the system

While this equation outputs a single figure, its variables range based upon varying local conditions. To account for this variance, "best case," "average case," and "worst case" scenarios were calculated by varying each variable based on their ranges outlined below. For thermal systems, this does not represent the best or worst possible theoretical scenarios, but rather scenarios based on historical generation data. To better understand and quantify which parameters have the greatest effect on each technology's LCOE, a sensitivity analysis was also performed by varying one input across its range while keeping other variables constant.

3. Results

3.1. Energy resource potential and capacity factor

3.1.1. Solar

The c-Si reference cell data and interpolated sunshine hour data, identified in Table 1, resulted in annual insolation values ranging from 1288 kWh/m^2/year in the east region to 1813 kWh/m^2/year in the north. GIS software visually identifies areas to target for solar PV, specifically in the north and west in Mauritius, as seen in Fig. 4. Applying a 5.7% increase from tilting the panels 20.3° north yielded an average CF of 18.5%, ranging from 15.5% to 22% (see Table 2). Applying a 21.3% increase from single axis tracking at 20.3° yielded a CF of 22.5%, ranging from 18% to 26%. Since solar PV global average CFs range 17–18% [24], solar potential in the north and west regions in Mauritius can be considered above average. Solar PV's 0.5%–1.0% degradation per year directly corresponds to its 20–30 year lifespan, defined as the years which it generates at least 80% of its first year total.

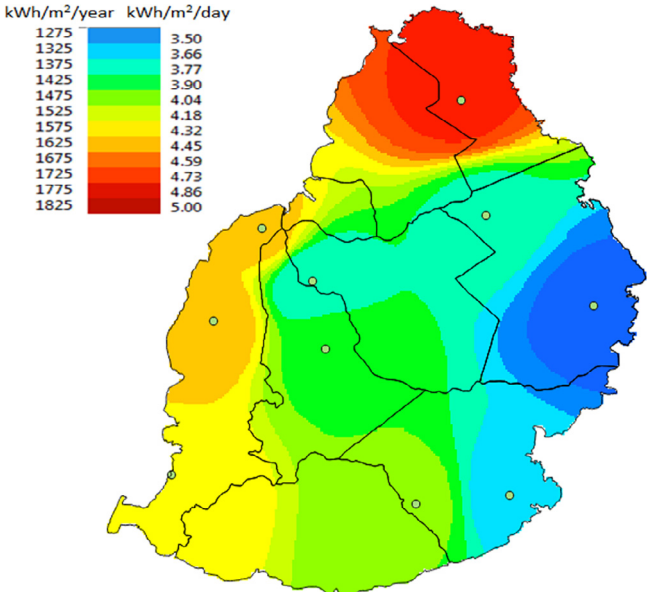

Fig. 4. Solar insolation in Mauritius.

3.1.2. Onshore wind energy

The wind dynamic in Mauritius is largely influenced by the southeast trade winds, which blow from the southeast in the Southern Hemisphere and are stronger, on a seasonal average, during the winter than summer. In Mauritius wind speeds were determined to average between 6 and 6.75 m/s at 66 m height in most locations along the southern and eastern coast, and 6.75–7.5 m/s at the same locations at 110 m [11]. While this data was primarily obtained from University of Mauritius researchers, their results were also confirmed by the wind resource studies from two local wind farm developers which identified average wind speeds of 6.4 m/s at 60 m height in island center and 6 m/s at 65 m in the east [39,40]. It is generally accepted that wind speeds above 6 m/s are required for viable wind turbine development, but wind speeds of 6–7 m/s would yield only a relatively low wind regime.

Applying wind speeds of 6–6.75 m/s to the Gamesa G58 850-kW 60 m wind turbine power curve resulted in CFs ranging from 17.4 to 21.6%, and 6.5–7.25 m/s applied to the Suzlon S95 2.1 MW 90 m wind turbines yielded 21.1–26.7% after factoring in typical system losses of 18% [13]. Therefore, depending on an onshore wind turbine's height, its likely CF ranges from 17.4% to 26.7%. This range confirms Mauritius' lower wind regime in comparison to the global average of 29% in 2017 [24].

Table 1
Reference cell and interpolated solar insolation.

Geographic Region	Location	Daily Sunshine Hours	Reference Cell Insolation (kWh/m^2/yr)	Interpolated Insolation (kWh/m^2/yr)
North	Cottage/Pamplemousses	7.79	1813	–
West	Medine	7.59	–	1688
South-West	Case Noyale	7.46	–	1605
South	Mare Tabiac	N/A	1513	–
Center	Vacoas	7.29	–	1500
Center-West	Reduit	7.14	1405	–
Southeast	Plaissance	6.98	–	1375
Center-East	Brisee Verdiere	N/A	1425	–
East	Belair/FUEL	6.53	1288	–
Average		N/A	1543	

Table 2
Input Ranges for Energy Generation Variables in the LCOE equation.

	Net Capacity Factor			Degradation	Lifetime
	Worst Case	Average	Best Case	%/year	years
Wave (CETO 6 tech.)	24.6%	28.7%	32.8%	0.75–1.75	15–25
Wind (Offshore)	45.0%	47.5%	50.0%	0.75–1.75	15–25
Wind (Onshore	17.4%	22.1%	26.7%	0.75–1.75	15–25
Solar PV (SSDG)	15.5%	18.6%	21.9%	0.5–1.0	20–30
Solar PV (Utility Fixed)	15.4%	18.4%	21.7%	0.5–1.0	20–30
Solar PV (Utility Tracking)	18.5%	22.1%	26.0%	0.5–1.0	20–30
WtE (Landfill Gas)	71.0%	67.8%	66.1%	0.25–0.75	10–15
WtE (Gasification)	67.0%	78.6%	91.1%	0.25–0.75	25–30
Biomass (Bagasse)	22.8%	35.1%	58.5%	0.25–0.75	30 -35
Bagasse-Coal (Seasonal)	73.8%	79.2%	85.2%	0.25–0.75	30 -35
Coal	78.8%	82.9%	87.1%	0.25–0.75	30–35
Heavy Fuel Oil	23.6%	34.5%	51.6%	0.25–0.75	30–35

3.1.3. Offshore wind energy

The MRC's offshore wind maps at 80, 90, and 100 m height provide initial insight into the potential for offshore wind in Mauritius. At 80 m height, the south-eastern coast displays a wind power density of 420 W/m^2, 2.3–3.4 times greater than the onshore wind power density at 66 m. At 100 m, areas close to the south and northeast coastlines display power densities of 450 W/m^2, 1.8–2.5 times greater than onshore wind power density at 110 m. According to offshore wind experts, this wind regime would likely result in CFs from 45 to 50%, which is in the high end of global offshore wind average CFs ranging from 40 to 50% [24,41].

3.1.4. Wave energy

While tidal energy is the most mature and developed ocean energy technology, wave energy has significantly more global resource potential in a wide range of locations [21,42]. With 330 km of coastline and a vast ocean area, large potential exists in Mauritius and early reports have indicated that while low potential exists for tidal systems, significant potential exists for wave energy. The MRC's preliminary study yielded a wave power density of 15 kW/m and Carnegie Clean Energy's more detailed wave buoy study yielded 20 kW/m along the south-eastern coastal region. This is within the optimal range of 15–35 kW/m for wave energy devices, and thus Mauritius can be considered to have average potential [43,44].

Determining a likely CF is challenging for a new technology with limited run time in various wave energy regions. However, applying a power density of 15–20 kW/m to IEA's Ocean Energy Systems graph of gross CF versus power density yielded gross CFs between 25% and 40%. Since Carnegie Clean Energy is currently working to develop a wave energy array in Mauritius and estimated their CETO 6 technology to perform in the higher end of that range, the gross capacity factor for wave energy system in Mauritius was estimated to range between 30 and 40%, and net CF between 25 and 33% after factoring in system losses.

3.1.5. Municipal solid waste

MSW, landfilled at Mare Chicose, in Mauritius has been increasing annually due to improved collection of waste and increasing population, and now averages around 1200 tons per day, or 438,000 tons per year [15]. While a 3 MW LFG plant currently utilizes the first six cells at the landfill, its energy generation peaked in 2014 once cell six was filled, and its seventh and final cell is set to reach full capacity by the end of 2018. Assuming this is typical of a LFG landfill project in Mauritius, its overall energy and corresponding CF decreases over the later part of its 10–15 year lifetime, with LandGEM gas and electric fitted data outputting an overall average CF of 61%. Therefore, with Mauritius' target to prioritize waste sorting and recycling facilities and a large-scale WtE plant, the energy potential may be limited to WtE gasification or incineration.

The composition of MSW in Mauritius is nearly 70% kitchen and garden waste and 25% paper and plastic due to extremely limited recycling [45,46]. Therefore, the waste has high moisture content but also a high dry caloric value after treatment. While the caloric value for unsorted waste has been reported between 6.7 and 13.5 MJ/kg with 45–55% moisture, its caloric value after treatment was confirmed by a gasification expert to range between 15 and 17 MJ/kg since its mass decreases by 55% [46]. Therefore, with a plant efficiency of 22% including parasitic loads, estimated from gasification plant personnel and confirmed by WtE studies [36,37], and standard availability of 85%, equations (3) and (4) result in 831 kWh per ton of treated waste and 165 GWh per year. Since the proposed plant has a power capacity of 24 MW, this would translate to an average CF of 79%, which is typical of thermal WtE plants.

Gasification plants were estimated to degrade 0.25%–0.75% per year, and was assumed to be similar across all thermal plants due to wear and tear, such as compressor fouling, surface degradation, start-up and shutdown frequency, and instrument misalignment [31,33–35].

3.1.6. Sugar cane – bagasse and cane trash

As sugar cane land decreased over the past few decades, bagasse generation still increased due to a shift from decentralized, less efficient generation at multiple plants to centralized production at large plants such as Terragen's Centrale Thermique de Belle Vue, commissioned in 2000, and Omnicane's La Baraque plant in 2005. Further centralization potential is planned with Alteo's upgrade to its F·U.E.L plant to 65 MW bagasse and 72 MW coal capacity after its PPA expires in 2018. Utilizing high efficiency boilers operating at high temperatures, 535 °C, and high pressure, 90 bar, as well as turbo alternators for exhaust steam can also increase output power [18]. This upgrade has the potential to produce an additional 100 GWh during bagasse production, according to a CEB representative.

Utilizing cane trash, the dry residue left after cultivation, can also increase electricity from bagasse. Terragen's pilot projects in 2015 and 2016 yielded 10 tons of cane trash per hectare of sugar cane, or 14 tons of cane trash per 100 tons of sugar cane [17]. However, to maintain healthy soil with cane trash coverage, only 50% of cane trash can be utilized for energy production. Therefore, the maximum theoretical potential of cane trash is 250,000 tons over Mauritius' approximately 50,000 ha of sugar cane [15]. In terms of energy potential, Terragen's project indicated caloric values of its cane trash at 13.47 MJ/kg at 15% moisture, and bagasse at 7.24 MJ/kg at 50% moisture. Both bagasse and cane trash caloric values and mass ratios are typical of global sugar cane production

[47–49]. Applying average bagasse power plant efficiencies from 2005 to 2015, 21.2%, and cane trash's caloric value to equation (3) results in 795 kWh per ton of undried cane trash. Therefore, with 250,000 tons of cane trash, an additional 200 GWh of renewable electricity could be generated. Therefore, increased centralization, efficiency, and cane trash could achieve Mauritius' Long Term Energy Strategy goal of increasing electricity exported through bagasse from 350 GWh to 600 GWh by 2025 [1].

3.1.7. Geothermal

Mauritius was formed through volcanic eruptions and had been thought to share the same magmatic source as Reunion, a French island 225 km west of Mauritius with favorable geothermal conditions. Mauritius' Ministry of Energy & Public Utilities therefore explored the geothermal potential in Mauritius through geological, geochemical, and drilling studies. The geological study indicated a heat source likely very deep, which was confirmed by an exploratory hole drilled in 2013 yielding a temperature gradient of 40 °C/km [20]. With a gradient which is only 1.3 times the normal geothermal gradient, a depth of 5 km would be required to achieve the 200 °C temperature required for most geothermal flash plants. Therefore, geothermal potential was determined to be unfeasible and was not further addressed.

3.1.8. Hydro

Hydropower has long been an essential part of Mauritius' electricity supply since its first power station, Tamarind Falls, was built in 1945. But as electricity demand has continued to rise in the past 25 years, hydropower has not been able to keep up. Today, according to the Ministry of Energy and Public Utilities, the hydropower potential is essentially fully tapped, leaving only small potential for micro-hydropower stations that operate in accordance with seasonal rainfall [50]. The growing need for household water and agriculture irrigation has also been identified as taking precedence over additional electrical generation plants, and therefore hydropower's LCOE was not addressed.

3.2. Capital, operational, and fuel costs

Similarly with the importance of identifying local data for country specific energy potential, local cost structures were identified to accurately portray Mauritian specific costs. Utility-scale solar PV capex for Mauritius in 2018 was determined to range from $1100/kW to $1250/kW and opex from $12/kW/year to $14/kW/year, as seen in Table 3, for a 5–15 MW farm, with single axis tracking systems increasing both capex and opex by 20–25%. These costs are lower than the 2017 global average of $1400/kW [24]. Residential systems of 1–3.5 kW range from $1791/kW to $2216/kW, with the lower end representing larger systems with string inverters designed at the maximum allowable 3.5 kW under the small-scale distributed generation (SSDG) scheme and the higher end systems with higher quality panels, maximum power point trackers, and smart technology. Opex for residential systems was assumed to be minimal, at half the relative cost of utility-scale systems, and based only on maintenance costs by the home owner.

The local capex for onshore wind was determined to range from $2175/kW to $2327/kW, significantly higher than the global average of around $1500/kW [24], due to high import and transportation costs of turbines and construction equipment, an underdeveloped Mauritian road system, immature local market, and their relatively small system size. Opex ranges from $55/kW/year to $64/kW/year, falling within global averages, from $41/kW/year in Finland to $76/kW/year in Japan [24]. While non-OECD countries typically have lower opex than OECD countries, plant representatives attribute slightly higher opex to overseas personnel and labor.

Offshore wind capex was estimated to vary from $4500/kW to $5500/kW, higher than the global average of $4500/kW [24] due primarily to significant transportation costs. The opex range from $120–160/kW/year is in line with the global market, and was estimated from the previously mentioned offshore wind expert that accounted for relatively close distance to shore and lower labor rates, but, as with onshore wind, also a smaller sized system, imported maintenance equipment, and overseas personnel [24].

Wave energy's best case capex scenario of $4000/kW is indicative of the lower range of a commercial scale 10–20 MW project estimated for CET0 6 technology potentially being piloted in Mauritius. Wave opex was estimated at $150/kW/year to $250/kW/year according to international reports [21,22].

Local LFG capital costs average $1771/kW, or 17–19% of capex per year, which is higher than global averages. For WtE gasification, its capex of $6500-$7000/kW falls in the higher end of global ranges from $2000-$7000/kW [24]. This reported average includes gasification for all biomass sources, so it is reasonable for a MSW plant to require a higher capital investment due to additional sorting, treating, and pollutant reducing technologies. While LFG opex was identified as a fixed cost around $300/kW/year, gasification opex was reported as a fixed $228–302/kW/year plus variable $3.5–4.5/MWh.

Bagasse-coal plants average $1944/kW, which is significantly higher than the global average capex range for co-firing plants, below $1000/kW, but within the capex range of biomass power generation in developing countries [24,27]. Capex for bagasse only plants was assumed to be similar due to insufficient data from the sole bagasse only plant. Coal plants' capex in Mauritius averages similarly, at $1867/kW, and is lower than US and UK markets, between $2250–3000/kW [23]. Local fuel oil plant capex average

Table 3
Economic variable inputs ranges for LCOE equation.

	Capex	Opex		Fuel	Discount Rate
	$/kW	$/kW/yr	$/MWh	$/MWh	% (Nominal)
Wave (CETO 6 tech.)	4,000–6,000	150–250	N/A	N/A	9.5–11.0
Wind (Offshore)	4,500–5,500	120–160	N/A	N/A	8.5–10.0
Wind (Onshore	2,317–2,479	55–64	N/A	N/A	7.5–9.0
Solar PV (SSDG)	1,822–2,405	6 -7	N/A	N/A	7.5–9.0
Solar PV (Utility Fixed)	1,350–1,500	12–14	N/A	N/A	7.5–9.0
Solar PV (Utility Tracking)	1,654–1,838	15–18	N/A	N/A	7.5–9.0
WtE (Landfill Gas)	1,605–1,774	273–337	N/A	N/A	8.5–10
WtE (Gasification)	6,500–6,700	228–302	3.5–4.5	N/A	8.5–10
Biomass (Bagasse)	1,623–2,086	72–79	4.9–5.8	(2.6–4.0)	7.5–9.0
Bagasse-Coal (Seasonal)	1,623–2,086	72–79	4.9–5.8	28–53	7.5–9.0
Coal	1,692–1,870	72–79	4.9–5.8	63–80	8.5–10
Heavy Fuel Oil	2,054–2,270	N/A	16.1–17.7	106–130	7.5–9.0

$2219 and opex around $17/MWh, according to a CEB representative.

Fuel oil's fuel costs average $118/MWh, while coal was significantly cheaper at $72/MWh. In Mauritius the same company runs both the sugar cane mill and power plant, so bagasse becomes a 'free' fuel as a by-product of sugar cane milling and power producers are even paid a fixed price, known as the 'bagasse transfer price' (BTPF), from the CEB per unit energy bagasse produced. Therefore, bagasse plants actually received a profit of $3.3/MWh from the BTPF, and therefore lowered total fuel costs for bagasse-coal plants to $44/MWh.

Mature utility-scale renewable energy systems are financed using overseas financing, and developers reported an average prime lending rate around 6.25%, and with 2% inflation, nominal discount rates of 8.25%. For less developed and more expensive ocean energy systems, even though socially and politically accepted, their high economic risk is a significant factor for their high lending rate. The higher environmental and social risk with MSW technologies also result in slightly higher discount rates in comparison to cleaner technologies. And while coal and fuel oil are both well established in Mauritius, recent protests and environmental concerns over coal increase its risk and corresponding discount rate.

3.3. *Levelized cost of electricity*

Each technology's cost-effectiveness in Mauritius was based on its LCOE relative to local fossil fuel systems and CCOE in 2017, $166/MWh. While the CCOE represents the retail market, and wholesale prices are lower, the CCOE can still provide a valuable reference for local rates. While best, worst, and average case LCOEs were calculated and visually represented in Fig. 5, for simplicity their average LCOE was used for comparison. The average LCOE of bagasse, solar PV, and WtE are below the average CCOE, and it is especially notable that bagasse, utility-scale solar PV, and LFGs LCOE are not only lower than coal's LCOE, but also lower than fuel oil's combined operating and fuel costs. Utility-scale fixed solar PV and bagasse have the lowest average renewable LCOE at $102/MWh, with bagasse-coal plants even as well at $102/MWh. For WtE systems, while LFG has a lower LCOE than gasification, they can both provide cost-effective solutions so their respective environmental impact could take priority. There is not a notable difference between fixed tilt and tracking solar PV, at $102/MWh and $104/MWh respectively. Smaller rooftop solar PV systems are not as cost-effective as utility-scale due primarily to higher capital costs per kW. Both onshore and offshore wind's average LCOE are slightly above the CCOE, and while not considered cost-effective for 2018, are projected to become more competitive with future price declines. The highest LCOE with the greatest range belongs to wave energy, as with such an immature technology, high costs are typical and CFs can vary widely.

It can also be useful to compare the local LCOE to a technology's global average to better understand its relative competitiveness on the global market. The LCOE for both utility-scale and residential solar PV are in line with 2017 global averages [24]. Wind energy is significantly less economic than global averages, around $110/MWh higher for onshore wind and $60/MWh higher for offshore, due to higher capex for both technologies and lower CF for onshore wind [51]. For WtE systems, gasification is in-line with global averages while LFG is around $40/MWh higher, potentially due to not collecting a gate fee and its low CF [23,51]. Fossil fuel economics vary widely around the globe depending if it is a local or imported fuel. Since Mauritius imports all of its coal, it may be reasonable that its LCOE is around double global averages [23]. It also makes sense that its fuel oil's LCOE of $216/MWh is in line with global averages since the market is largely made up of SIDS.

Each energy system's LCOE varies based on their input parameters, and a sensitivity analysis helps to identify which parameters are most impactful. For renewable energy systems, their CF has the highest effect on their LCOE, as shown in Fig. 6. For variable renewable energy systems, this means that an above average resource is a key indicator for a cost-effective system. For firm renewables, a low CF usually means an oversized system. This is especially noticeable for bagasse, whose LCOE can increase by over 50% if its CF reaches as low as 23%, as reported from a local bagasse plant. Similarly for fuel oil systems, their CF is most impactful, signifying the different economics of a base load plant with a high CF versus a peak demand plant with a low CF. For coal systems, fuel costs impact their LCOE the most and signify their susceptibility to future fluctuations in fuel prices.

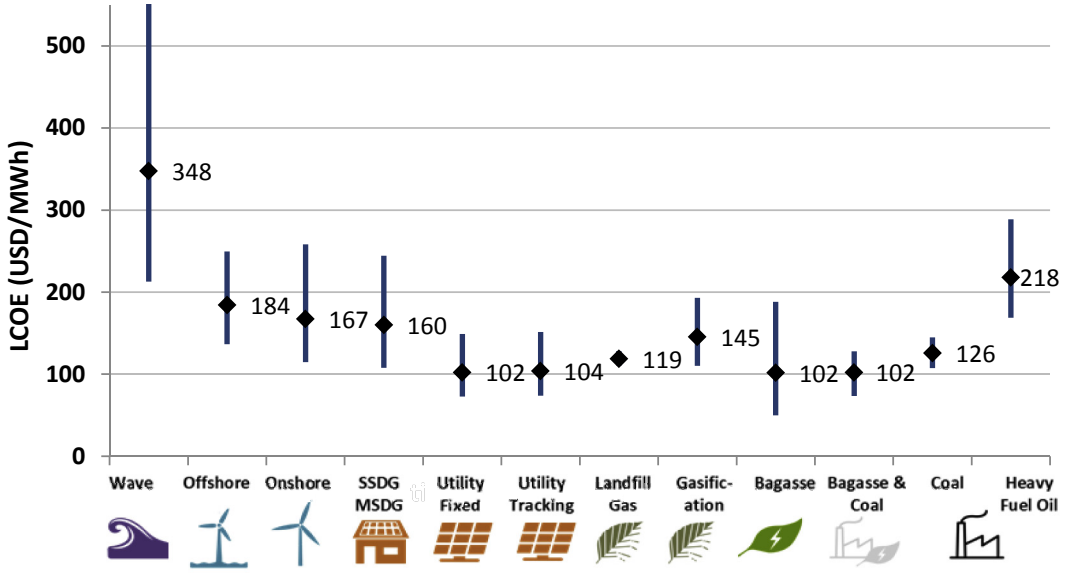

Fig. 5. LCOE of energy technologies in Mauritius.

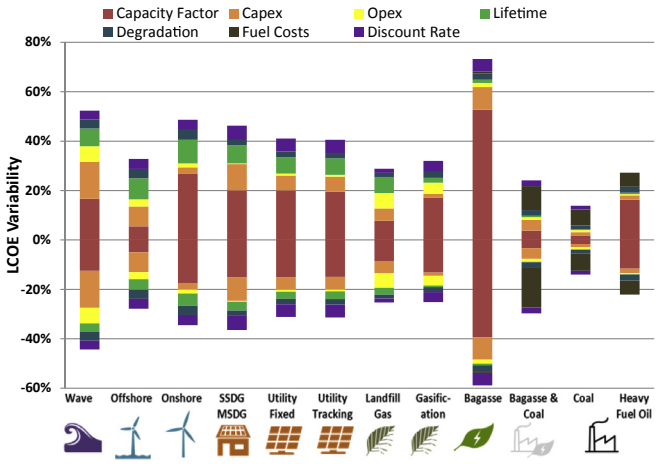

Fig. 6. Sensitivity analysis of LCOE variables.

3.4. Discussion and limitations

The LCOE has been shown in this research to be a powerful metric for comparing the cost-effectiveness of various technologies, but also has numerous limitations that should be considered during holistic renewable energy planning. A primary limitation of the LCOE is its inability to distinguish between intermittent, variable, baseload, and peak demand plants. Therefore, LCOE does not portray real world energy markets with real time pricing signals where technologies that can generate on demand are compensated accordingly. And as Mauritius' peak demand continues to increase, even non-generating mechanisms such as energy efficiency and demand response that are not valued in a typical LCOE study are essential to cost-effectively address peak demand. Similarly, LCOE does not incorporate potential additional costs from frequency regulation storage or load shifting storage required for grid stability and reliability when variable renewables reach high penetration levels.

Other aspects outside of the scope of an LCOE analysis, particularly relevant to SIDS, involve land constraints and grid resiliency. While land constraints do directly tie into higher capex from expensive land leases, further analysis is required to determine land available for utility-scale solar PV and its corresponding maximum feasible energy potential. And although a sensitivity analysis quantifies how fuel price ranges impact costs, the LCOE does not value technologies that are economically resilient from fuel spikes, or, with SIDS especially vulnerable to tropical storms, climate resilient.

Lastly, this LCOE analysis did not address various financing mechanisms or indirect costs. The discount rate does enable LCOE to value lower risk technologies but does not portray different financing mechanisms outside of debt lending or the barriers of access to capital for large utility-scale technologies, both renewable and non-renewable. This LCOE analysis also focused entirely on direct costs, while other indirect costs, such as environmental and health costs, are necessary to include for holistic energy planning. While this study deliberately chose not to quantify these costs since the majority of IPPs will not be compensated accordingly, these indirect costs can be incorporated by including the social cost of carbon as an operating expense.

3.5. Conclusion and recommendations

This paper utilizes the LCOE to prioritize cost-effective energy technologies, and the methodology presented can serve as a model for other agencies attempting to cost-effectively transition to renewable energy. This research specifically assists Mauritius policy makers and its public utility by providing three primary findings. The first major takeaway is that Mauritius is an island full of renewable energy potential. Its solar radiation and offshore wind speeds are especially high relative to global averages. The caloric value of untapped biomass, in sugar cane trash and MSW, is sufficient to significantly increase electrical generation. While its wave energy resource is moderate, potential still exists for generation in optimal conditions. However, while onshore wind speeds are technically sufficient for wind turbine generation, they are low relative to the global market, thus translating to a low CF and high LCOE.

The second key finding is that, in the case with solar PV and bagasse, when an above average renewable resource is combined with a low-risk technology with competitive capital and operating costs, renewable energy's LCOE is not only lower than coal's LCOE, but also lower than current costs to operate a fuel oil plant. Therefore, for Mauritius to achieve its renewable energy targets while reducing consumer electricity rates, it is recommended to target solar PV and bagasse while retiring fuel oil plants. However, given land constraints, as bagasse and solar PV maximize onshore generation potential, offshore wind could also provide a viable solution, as their costs are predicted to continue to fall to where their future LCOEs would be competitive with local energy costs.

While the average LCOE provides relevant comparisons between technologies, the large LCOE ranges from best to worst case convey their high sensitivity to the input variables. The last important finding identifies the most impactful LCOE input variables so that their variability can be limited. Fuel costs have the highest impact on fossil fuel's LCOE, and therefore increasing renewable generation should further isolate consumers from future price fluctuations. A renewable energy system's CF has the highest impact on its LCOE, therefore it is recommended to provide developers with accurate wind, solar, and wave resource maps to improve energy output, increase investor confidence, and further de-risk projects.

As Mauritius transitions to a higher penetration renewable energy grid, future research is recommended to address the LCOE limitations identified as outside this research scope. With higher shares of variable renewable energy, research is required to determine how to cost-effectively ensure reliability and resilience through storage, smart grids, and other technologies. Since renewable energy share is simply annual renewable generation per annual demand, and Mauritius' peak annual demand continues to increase, additional research could also investigate the cost-effectiveness of implementing large scale energy efficiency and demand response to reduce demand and increase the share of renewable energy.

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